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Fly's-Eye Lens Technique for Generating Semiconductor Device Fabrication Masks*

This Communication describes an improved method for fabricating multiple-image photographic masks of high quality. Photographic masks are commonly used in the fabrication of silicon transistors and diodes. Such masks are needed in sets of five, ten, or even twenty, each being used for one of the steps in the photoengraving-type fabrication process. Arrays of many devices are made at one time on a silicon wafer. The photographic masks are the corresponding arrays of microscopic images. Figure 1 shows a portion of two representative transistor masks. The center-to-center distance between the devices may typically be 0.020", 0.025" or 0.030", with a total of perhaps 1000 devices in the array.

Aside from the obvious requirement of excellent photographic image quality, the major problem in the generation of a set of masks is to insure precise mask-to-mask registration. Every spot on one mask must register with the corresponding spot on every other mask. For example, one mask may involve black stripes 0.0005" $\times$ 0.0030".

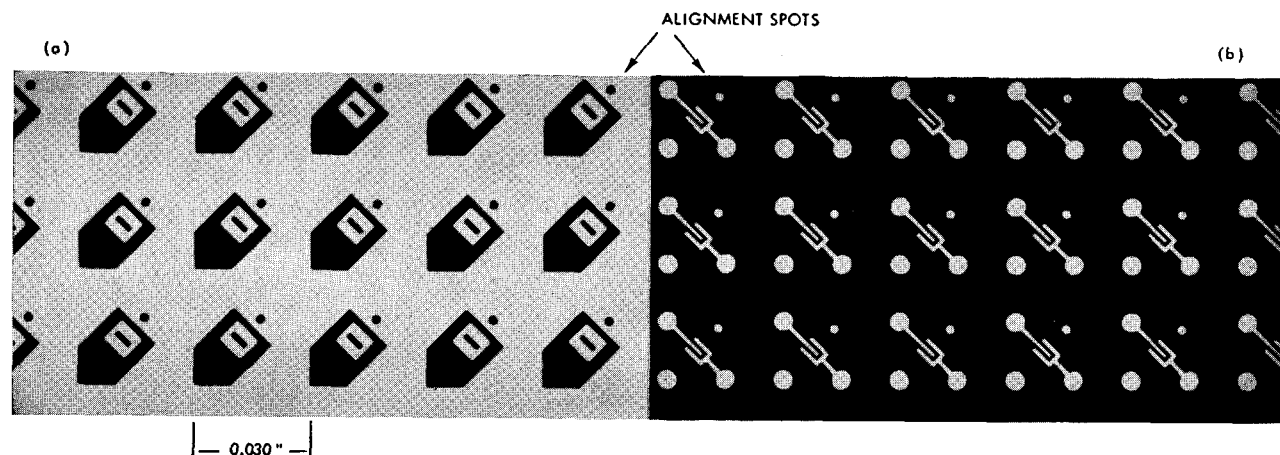
Suppose that the silicon wafer is one inch in diameter, and that the mask has been positioned over the wafer so that the black stripes on the mask coincide exactly with the visible, partly finished devices on the wafer. If the stripe corresponding to a device in a certain location deviates from its proper position by as little as 0.0002", the mis-registration is nearly half the width of the stripe and might ruin the device, perhaps by uncovering a junction.

Until this time, essentially all photographic masks of this type have been made by a process of step-and-repeat. Either the array of images is generated at many times the final size, and then photographically reduced to make the actual mask, or the step-and-repeat process is done at the final size.¹ In general, the step-and-repeat process must be performed for each mask in the set. The mask-to-mask registration of such a set, the importance of which is described above, depends on several variables which affect registration: the accuracy of the step-and-repeat camera, the skill of the operator, and the precision of the final reduction.

In addition to the problems of registration are the considerations of cost and time. It takes at least several

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Figure 1 Portion of representative fly's-eye masks used for silicon transistor manufacture. a) Photographic mask for emitter diffusion. b) Photographic mask for subtractive etch of contacts.



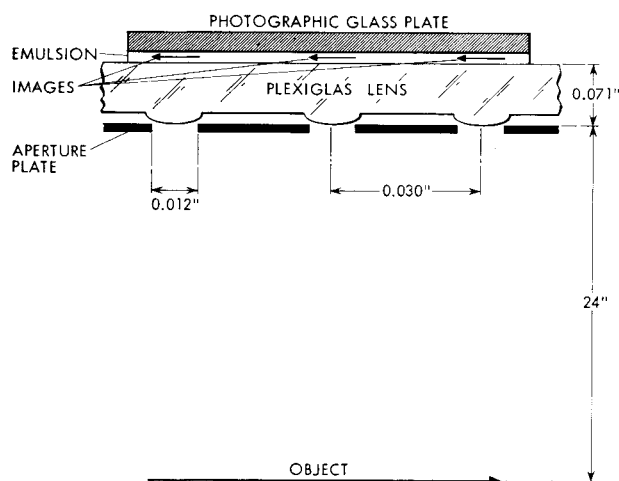


Figure 2 **Schematic drawing of fly's-eye principle.** Dimensions shown are representative but not drawn to scale.

days to generate a set of masks by this step-and-repeat technique, and in practice it may take three or four weeks to get a new set of masks. Costs are correspondingly high, in the order of thousands of dollars for one set. Also, in the development of a process it is frequently found, after a set of masks has been made and used, that an additional mask is needed. This mask must register with the original set, for wafers may already be in process. It is questionable whether or not the required additional mask, made by step-and-repeat, would register with the original set.

"Fly's-eye" principle

A novel process which overcomes all of these problems has been developed. The heart of this process is the "fly's-eye lens," actually an array of tiny lenses of short focal length. The size of the array and the distance between the lenses correspond very closely to those of the desired

mask. The theory is simple: each lens forms an image in the same focal plane. If an object is placed in front of the lens, and a photographic emulsion or other light-sensitive medium is placed in the focal plane of the lenses, an array of identical latent images is formed, as indicated in Fig. 2. The relative positions of these images depend only on the relative position of the lenses. The lens in Fig. 2 could be eliminated and the aperture used for a pin-hole camera.² However, experiments in our laboratory have shown that the resulting image quality is inferior to that achieved by the fly's-eye lens.

Lens design

A convex-plano lens designed so that the image is formed on the flat surface of the lens is described in this communication. The parameters are related by two equations:

$$\frac{n}{s} + \frac{n'}{s'} = \frac{n' - n}{R} \quad (1)$$

$$m = -\frac{ns'}{n's} \quad (2)$$

where

s is the object distance

n is the index of refraction in the object space

s' is the image distance

n' is the index of refraction in the image space

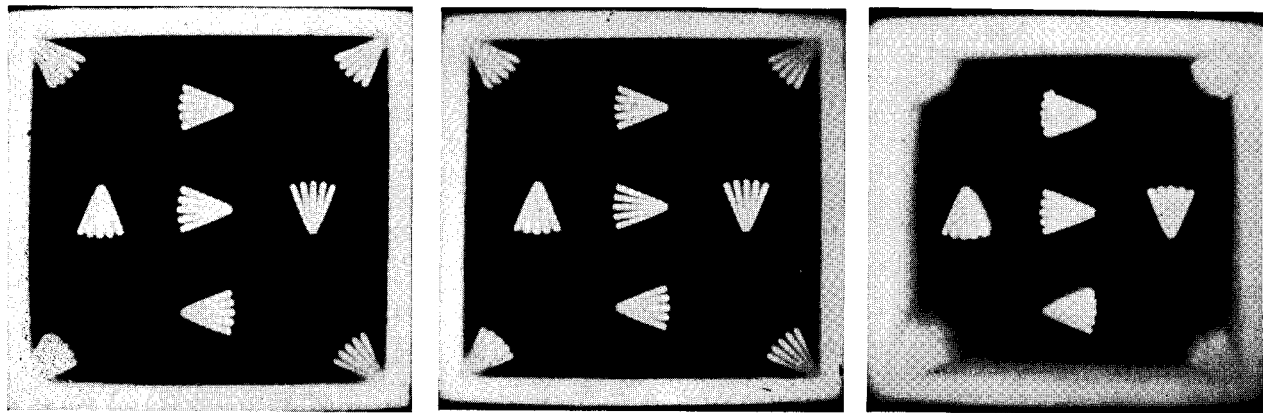
R is the radius of curvature of the refractive surface, and

m is the magnification.

As an example, consider a lens used for making transistor and diode fabrication masks on 0.030" centers. Here the object space is air, so that $n = 1$. The lens is molded of Plexiglas* having an index of refraction $n' = 1.49$. The radius R is chosen to be 0.0234". The desired magnification is $m = -(1/500)$. Substituting these values into (1) and (2) and solving for s and s' , it is found that the object distance is 23.96" and the image distance

* Trademark.

Figure 3 **Effect of aperture diameter on resolution.** From left to right: 8-, 12-, and 16-mil apertures.



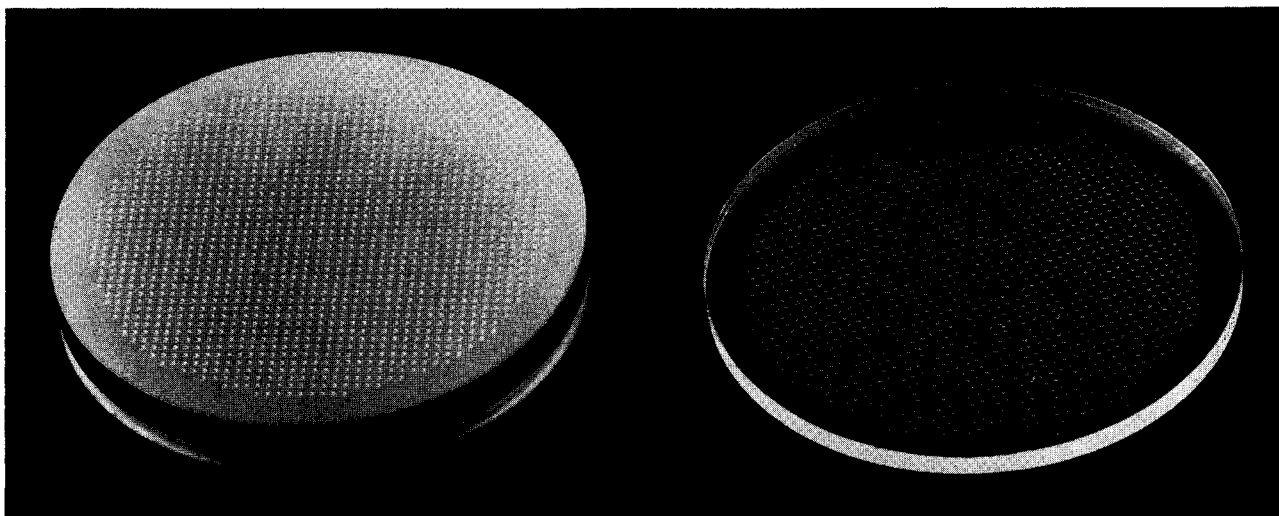


Figure 4 Indented copper disc (left) used for molding Plexiglas and fly's-eye lens (right) molded from this copper disc. The discs are 1.5 inches in diameter.

is 0.0714". The focal length is found by setting the object distance equal to infinity ($1/s = 0$) in (1). The focal length $f = s'$ ($1/s = 0$) is found to be 0.0713" in Plexiglas which, for practical purposes, is equal to the image distance. The depth of field is large, and a change in the object distance will not effect the focus but will effect the magnification.

The f /number is chosen to give maximum paraxial resolution. Experimentally this is found to be $f/4$, corresponding to an aperture 0.012" in diameter (see Fig. 3). The f /number is computed as the ratio of the equivalent focal length in air (focal length in Plexiglas/ n') to the diameter of the aperture. If the f /number is increased to $f/6$ (0.008" diam), there is a loss of paraxial resolution due to diffraction. Decreasing to $f/3$ (0.016" diam) results in a loss of resolution due to geometric aberration. Only paraxial resolution is discussed above. Off-axis resolution is limited by aberration and may be improved, at the expense of paraxial resolution, by increasing the f /number.

Lens fabrication

The mold for forming the Plexiglas lens is made from a highly polished copper block. An array of indentations is made with an instrument-grade, high-chrome steel ball having a diameter of $3/64$ ". The indentations are spaced 0.030" apart and have a depth of about 0.001" as is shown in Fig. 4. The work is done by placing the copper on an x - y micrometer stage and moving it beneath the indentation mechanism. The same ball is used for the entire mold. In this way about 1450 indentations are made with a positional error of 0.0001". However, note that registration from mask to mask in a set is not dependent on this positional accuracy. If one of the lenses in the array is displaced from its proper location in the array, the corresponding images formed by this lens will also be displaced, but all the images will be displaced in

exactly the same way and thus will register perfectly with one another. The only requirement, of course, is that the masks have the same orientation.

The lens is now formed by compression molding of a Plexiglas blank between the copper mold and a polished glass disc. The thickness of the lens is held as closely as possible to 0.071" by controlling the weight of material placed in the mold. Precautions are taken to minimize flashing of the material out of the mold. The glass insures a smooth, scratch-free surface on the back of the lens. By design, this is the focal plane.

The lens shrinks after molding³ so that the final spacing between lenses is 0.02994". The spacing of the images on the photographic plate is not quite identical to the spacing of the lenses. A simple calculation shows that a lens spacing of 0.02994" will result in an image spacing on the masks of 0.030". Each lens has its own optical axis. These do not coincide but are spaced 0.02994" apart. Moving from one lens to the next is equivalent to moving the pattern 0.02994" in the opposite direction. This movement is now reduced 500 times. If the object is moved 0.02994", the image moves $0.02994"/500$, or 0.00006". Adding this to the distance between the lenses gives 0.030".

An aperture plate is punched in 0.001" thick steel shim stock, which is then blackened to minimize unwanted reflection of light. The aperture plate is an array of holes 0.012" in diameter, spaced 0.02994" center to center. This is mounted directly in front of the lens and serves to determine the f /number of the lens. The aperture plate also prevents light from passing through the plastic between the bumps, causing unwanted fogging on the photographic plate.

Mask making

The fly's-eye process is fast as well as accurate. A single pattern, or a transparency, is cut at many times final size.

The pattern is then placed on a light box and a photographic plate is exposed through a fly's-eye lens. This plate, when processed, is the desired mask. Suppose, for example, that a device design engineer supplied sketches of five patterns and asks for three masks of each pattern. The patterns may be cut, the plates exposed and processed, and the set of fifteen masks placed in a drying rack within two hours.

Figures 5 and 6 show the equipment used for making masks. The light source used is an array of sixteen 100-watt incandescent light bulbs, about 18" square. A pattern 15" square placed on the light box will be reduced to an image 0.030" square. The 18" light box gives sufficient margin. In this way it is possible to make both positives (black spots on a clear background) and negatives (clear spots on a continuous black background) as shown in Fig. 1.

The patterns are cut from Studnite*, a sheet of transparent plastic laminated with a red (photographically opaque) plastic film. The thin red layer is cut and stripped off certain areas, leaving the remaining areas red on the thicker, clear base. Holes are punched in two corners of the Studnite patterns when they are cut. These are later used in conjunction with two pins on the light box to position the pattern accurately in front of the lens. The required precision of this positioning is not too great because of the 500-to-1 reduction.

A pressure diaphragm presses the glass plate against the flat back surface of the lens to insure good contact between the emulsion and the lens. Since the back surface is used for positioning, once the lens has been molded so that this surface and the focal plane coincide, the process is highly reproducible.

Four-by-five inch Kodak High Resolution Plates have been used. Developing time is two minutes in Kodak D-8. With this particular setup, exposure times of about 10 sec result in density and contrast suitable for the photo-engraving-type process.

The quality of the photographic masks produced by the fly's-eye lens is excellent. Resolution on the optical axes of the lenses is over 400 lines/mm, as shown in Fig. 7. Resolution does drop toward the edge of the unit cell. This is not important for transistors of the type shown in the illustrations, since the critical dimensions of the transistor are in the center of the unit cell and only the less critical contact land areas are located significantly far away from the center. For example, Fig. 8 shows deterioration of the edge definition in the outer regions of the pattern. Further, the small amount of barrel distortion, characteristic of this lens, is not important, since every mask made with the lens will be subjected to the same barreling.

Discussion

The fly's-eye lens technique does not allow conventional alignment spots to be placed accurately on the masks. The need for such spots is particularly important for

* Trademark.

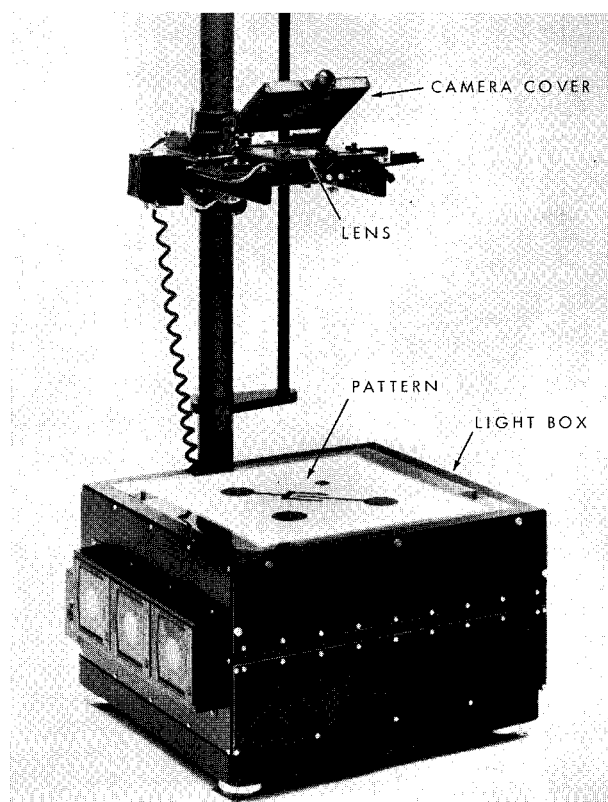
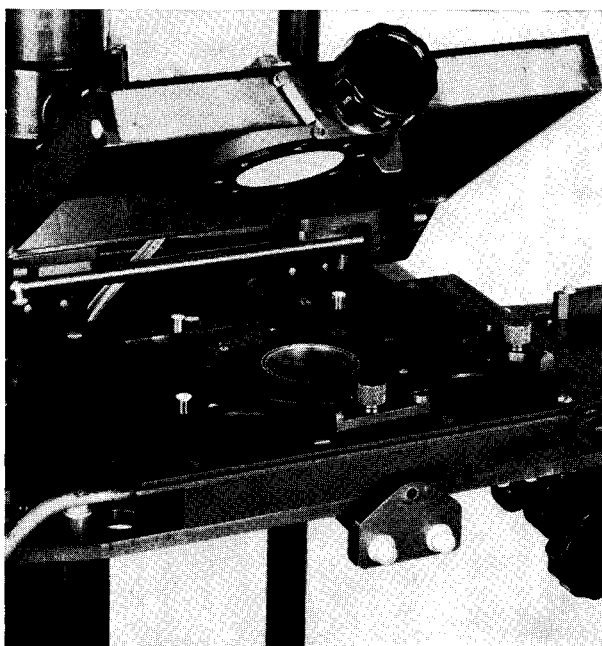


Figure 5 Fly's-eye camera and light box used for exposing masks.

Figure 6 Close-up of fly's-eye camera showing lens and pressure diaphragm.



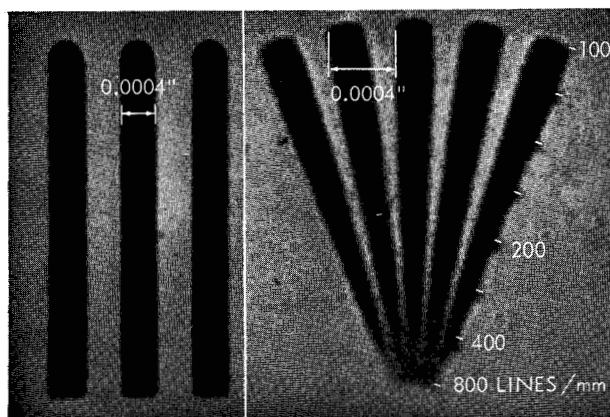


Figure 7 Test patterns showing resolutions and edge definition on optical axis.

negative masks (clear spots on a black field) where the patterns on the silicon wafer cannot be seen through the clear areas in the mask. This problem has been overcome simply by using alignment spots in every device location. These will be noted in Fig. 1, for example. The alignment spot is generally a circle or square, positioned near the outer edge or corner of the device. These circles are either larger or smaller than the circle on the previous mask (depending on whether the mask is negative or positive), so that the previous circle can clearly be seen and centered within the clear circle on a negative mask, or around the black circle on a positive mask.

It is possible to place more than one pattern on the same photographic mask. A simple stop is punched out of thin steel and placed in front of the lens array. The stop either covers a certain lens completely or not at all. A normal exposure is then made with Pattern A. The photographic plate is then left clamped in the camera, and only the stop in front of the lens and the pattern are changed. The lens and aperture plate are left undisturbed. Pattern B is then used to expose various parts of the plate which were not exposed to Pattern A. This method may be extended to any number of patterns.

In this way special patterns or alignment spots may be put in certain specific locations. Also, two or more different device geometries may be studied on the same wafer. Perfect mask-to-mask registration is inherent to the system.

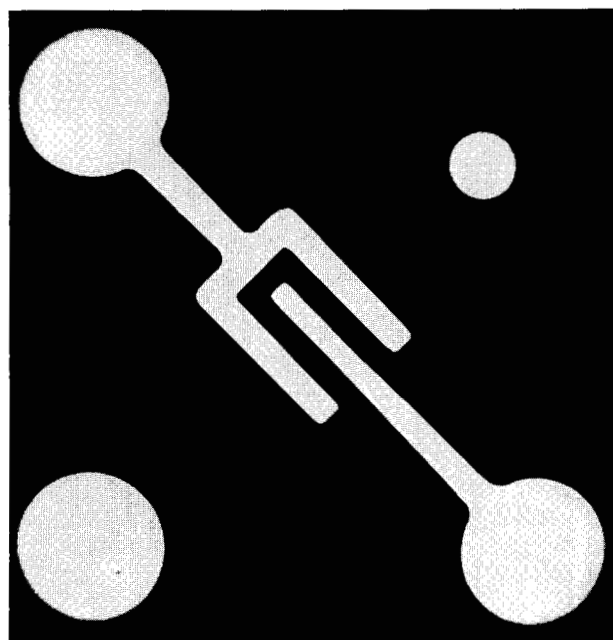


Figure 8 Enlargement of a single element of the array shown in Figure 1(b). Note the difference between edge definition in the central and off-axis regions.

Photographic masks have been made in large quantities by the fly's-eye lens and used in the manufacture of transistors and diodes. The fly's-eye lens has also been used to make positives for etching metal masks. Other uses are clearly indicated—for instance, in microcircuits and cryogenics. Finally, the use of the lens is not limited to photographic plates but may be used to expose any photosensitive material. The ultraviolet transmitting properties of Plexiglas are such that Kodak Photo Resist, for example, may be exposed directly.

References and footnotes

1. T. C. Helmers, Jr. and J. R. Nall, "Microphotographs for Electronics," *Semiconductor Products* 4, No. 1, 37 (1961).
2. J. J. Murray and R. Maurer, "Arrays of Microphotographs for Microelectronic Components," *Semiconductor Products* 5, No. 2, 30, (1962).
3. This shrinkage can be adjusted over a small range by controlling the molding pressure.

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